Free Air Breathing Planar PEM Fuel Cell Design for Portable Electronics

By

Ethan J. Crumlin

Submitted to the Department of Mechanical Engineering in
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ABSTRACT

PEM fuel cell technology is an energy source that can provide several times more energy per unit volume then current lithium ion batteries. However, PEM fuel cells remain to be optimized in volume and mass to create a minimum size for integration into portable electronics. A planar fuel cell design utilizes the bare minimum in volume and mass over current stacked fuel cell designs. This was done by taking an innovative approach of assembling the fuel cell with just the bare minimum components, a proton exchange membrane, cathode electrode, anode electrode, and gas diffusion layer on both sides of the membrane to assume the role of GDL and current collector. This planar fuel cell design was able to produce a power density over 25mW/cm2. This is an order of magnitude lower then reported air breathing fuel cell values, however the route cause has been isolated to the ohmic losses of the planar fuel cell. Increasing the applied contact forces and creating low resistance electronically conductive grid lines, have shown to contribute to the reduction in ohmic resistance and will be the focus of future research. From this research, a planar fuel cell design has been shown to successful work and there are ways to improve its performance.

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1 Fuel Cell Overview:

1.1 What is a Fuel Cell and how does it work?

A fuel cell is a device composed of only a handful of components and facilitates a somewhat simple electrochemical reaction. **Figure 1** depicts the parts used to make a fuel cell. There are three essential components to the design and several secondary components. The primary components are the electrolyte/membrane electrode assembly [MEA], the current collectors, and the fuel source; these are essential to running a fuel cell. Other components commonly used for varying purposes and designs are, gas diffusion layers [GDL], gaskets, heating and/or cooling elements.

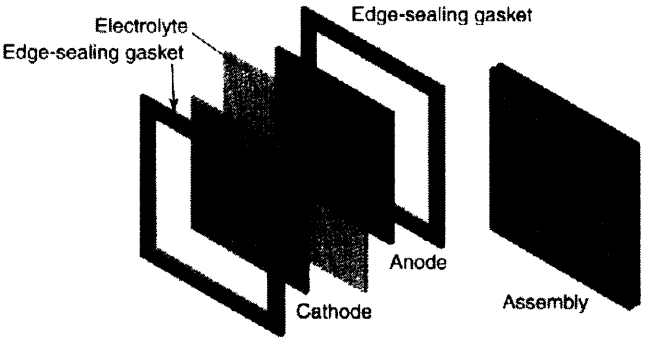


Figure 1: fuel cell assembly (Larminie, P. 11)

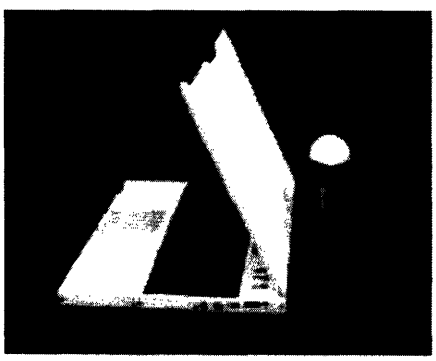
1.2 Current Fuel Cell Technology Available:

Fuel cell technology has been used in practice for decades, historically they were mainly in specialty applications and industries such as the space industry. Which was one of the only industries that could support the development, cost, and low enough use cycle to help avoid some of the long term robustness issues that were and still are prone with fuel cell technology. **Figure 2** shows a picture of one of Apollo's fuel cell systems that was used to provide electrical power and potable water to the craft that took man to the moon.

This success spawned substantial work and research in the alkaline fuel cell technology in the 1960's and 1970's, however with increased performance in PEM fuel cells, they have been the driving force and direction for most portable fuel cell technologies (Larminie, 122).

Figure 2: 1.5-kW alkaline electrolyte fuel cell from the Apollo spacecraft, supplying electrical power and potable water to the craft that took man to the moon (Larmine, P. 123).

There are three fuel cell technologies that are currently being aggressively researched and developed for a majority of applications. Direct methanol fuel cells [DMFC] which use liquid methanol as the fuel, which is a low operating temperature fuel cell making it good for small portable applications such as laptops and cell phones as seen in **Figure 3**.



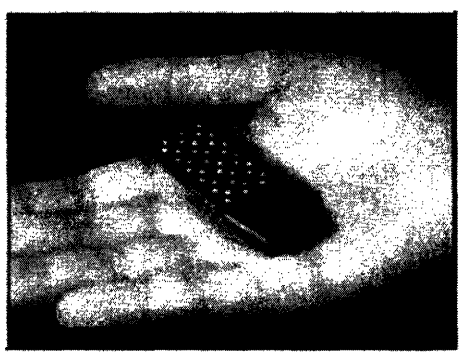


Figure 3 (left): NEC's direct methanol fuel cell laptop prototype [2]
(right): Toshiba's direct methanol fuel cell for cell phone applications [3].

For larger more industrial and stationary applications, solid oxide fuel cells [SOFC] are in development for there large capacity, efficiency and high temperature operating conditions. The most interesting potential with these SOFC's is there potential of being placed in large-scale power generation systems **Figure 4**.

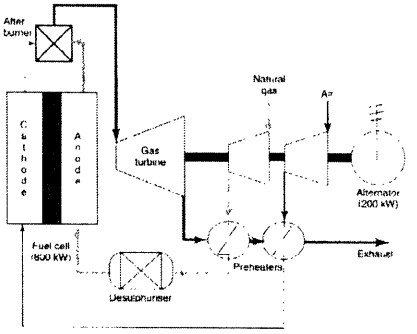


Figure 4: SOFC/GT power plant system diagram (Larminie, P. 223)

PEM fuel cells are the third and possibly the most versatile fuel cell technology, whose uses range from small portable applications to large scale commercial and industrial applications. PEM fuel cell technology is perceived to be even more useful then DMFC due to the increase in energy density by utilizing hydrogen as the fuel source instead of methanol. Current PEM fuel cell applications being tested range from military and space craft applications to new power platforms for luxury cars as seen in **Figure 5**.

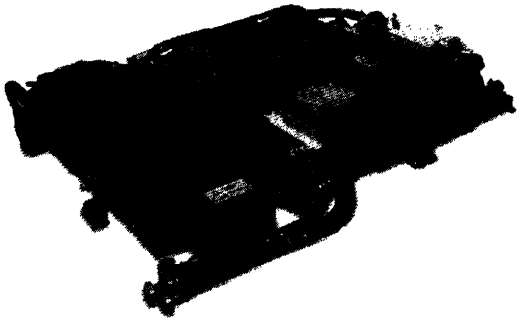


Figure 5: 75-kW fuel cell system prototype for a

Mercedes Benz A-class car (Larminie, P. 21)

2 PEM Fuel Cell Theory

To aid in explaining the history, analysis and discussion of fuel cells, it is important to understand a few basic fuel cell principles and performance characteristics, such as the electrochemical reaction that is occurring, open circuit voltage (OCV) and standard voltage vs. current (polarization curves) results. The OCV and polarization curves are very commonly used to evaluate fuel cell performance; the OCV can be used to gauge the kinetic efficiency of a fuel cell and the polarization results relay a great deal of information about the actual performance of your cell and its various limiting factors.

2.1 PEM Fuel Cell Electrochemistry

At the anode side of the fuel cell, where the hydrogen fuel source enters the fuel cell, the following reaction takes place: $H_2 \Rightarrow 2H^+ + 2e^-$; at the cathode side of the fuel cell where the oxygen fuel source enters the fuel cell the following reaction takes place: $2H^+ + \frac{1}{2}O_2 + 2e^- \Rightarrow H_2O$. **Figure 6** shows the reaction that occurs within a typical PEM fuel cell in more detail.

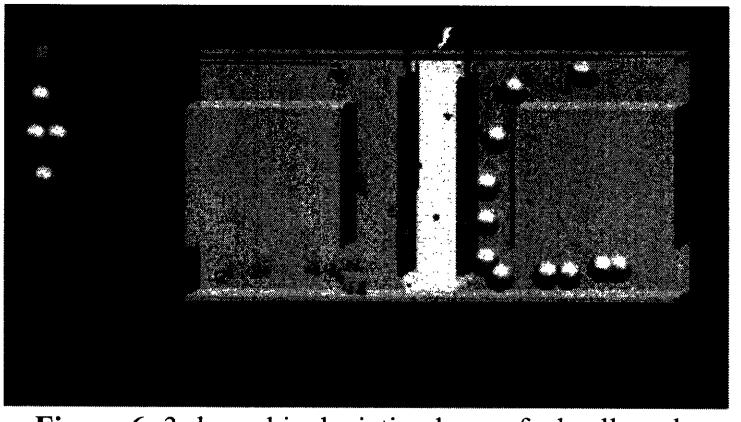


Figure 6: 3-d graphic depicting how a fuel cell works

These reactions occur in this fashion due to the MEA. The MEA is comprised of active catalyst areas on both sides of a proton exchange membrane (PEM), where the active catalysts are usually noble metals such as platinum or palladium. The active catalyst layer on the hydrogen side is used to facilitate the breakdown of H_2 into a proton and electron element. The protons are then allowed to pass through the proton exchange membrane to react with the oxygen fuel source on the other side of the membrane. The current collectors transport the electron charge from the anode to the cathode, providing an electrical power source as well as completing the reaction at the cathode side of the fuel cell.

2.2 Open Circuit Voltage (OCV)

To determine the theoretical OCV, we can begin by creating a relationship between the voltage of a fuel cell and the thermodynamics of the chemical reaction taking place. The maximum work of a fuel cell is governed by the voltage potential ε, and charge q_e:

$$w_{max} = \varepsilon q_e$$

Where the charge is

$$q_e = nF_a$$

n is the number of electrons transferred and $F_a = 9.6485 \times 10^4$ Coulombs is Farady's number.

The work can be determined by evaluating the thermodynamics of the fuel cell at ideal conditions defined by the products flowing out of the fuel cell at the same temperature and pressure of the environment. The maximum work in this instance is determined by calculating the Gibbs free energy of the reaction:

$$w_{\max} = \Sigma\Sigma G_r^{\circ} = \sum_{react} v_i(\hat{h}_i^{T_o,p_o} - T_o\hat{s}_i^{T_o,p_o}) - \sum_{prod} v_i(\hat{h}_i^{T_o,p_o} - T_o\hat{s}_i^{T_o,p_o})$$

Therefore, to find the ideal voltage, ε_o, at standard temperature and pressure, where all the reactants and products have a partial pressure of 1, the above equations can be set equal to each other and solved for the potential.

When dealing with a fuel cell that is not operating at 1atm and has no pure reactant and product streams, then the change in Gibbs free energy can be expressed as:

$$(\Delta G_r) = (\Delta G_r^{oo}) + RT\ln\left(\frac{p}{p_o}\right) + RT\ln\left(\frac{\prod_{react} X_i^{v_i}}{\prod_{prod} X_i^{v_i}}\right)$$

Where $\Delta_v = \sum_{prod} v_i - \sum_{react} v_i$.

Combining this expression for the change in Gibbs free energy with the expression for maximum work and its relationship to voltage yields the following equation called the Nernst equation:

$$E = E^{\circ} - \frac{\Delta_v RT}{F_a}\ln\left(\frac{p}{p_o}\right) + \frac{RT}{F_a}\ln\left(\frac{\prod_{react} X_i^{v_i}}{\prod_{prod} X_i^{v_i}}\right)$$

At 25°C and 1 atm, the OCV of a hydrogen-oxygen PEM fuel cell is approximately 1.23 volts, and a hydrogen-air PEM fuel cell is always lower then when the PEM fuel cell is operated using hydrogen-oxygen due to the 20% concentration of oxygen in air versus 100% when using pure oxygen. To get the actual OCV, reactant gases would be supplied to the fuel cell while the voltage difference between the anode and cathode sides of the fuel cell is measured. This can be measured with something as simple as a portable

digital multi-meter. The actual measured OCV is always less then the theoretical due to inefficiencies induced by some of the hydrogen crossing over to the cathode side and not being oxidized; in this even, hydrogen does not transfer charge, thus reducing the OCV. Dividing the measured OCV by the theoretical OCV yields one of the fuel cell's characterized efficiencies, often associated with depicting the fuel cells kinetics[4, 5].

2.3 Polarization Curves, Voltage vs. Current

To help quantitatively determine the performance of a fuel cell, a polarization curve is created. This is done by plotting the points for a range of voltages, usually from OCV to near zero, and recording the maximum current the fuel cell can source at each voltage. Conveniently, this also provides the power output of the fuel cell by simply multiplying the voltage and the current at each interval. Common convention for recording the current is by the fuel cell's current density [A/cm^2]; power is also expressed in the same fashion as a power density [W/cm^2], where the area that is referred too when discussing these densities are the areas of the active electrode. An example of a standard polarization curve is shown in **Figure 7**.

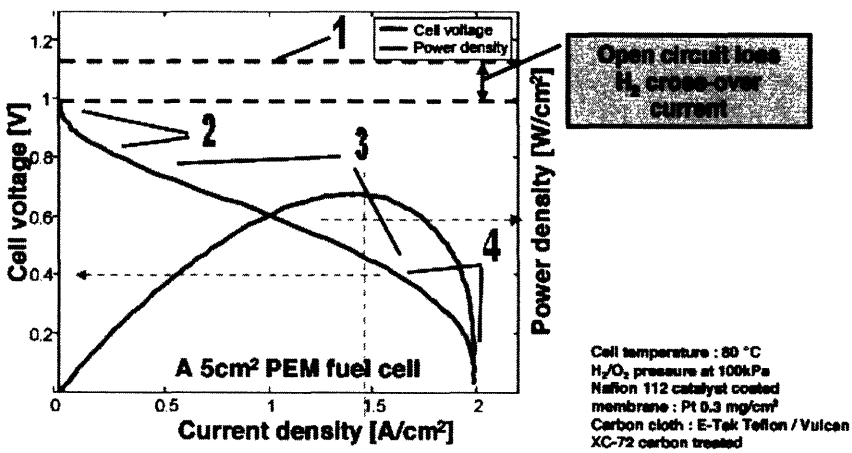


Figure 7: typical voltage vs. current results, (1) indicates the theoretical

OCV, (2) where the activation overpotential occurs, (3) the ohmic resistance effects, (4) mass transport limitation region[5].

The OCV, current density, and power density are not the only bits of useful information that can be extracted from the polarization curve. The performance of a fuel cell is reduced due to several limitations, hydrogen cross-over, activation overpotential, ohmic resistances, and mass transport losses, all of which are apparent from the curve as seen in **Figure 7**.

Hydrogen Cross-Over: creates the discrepancy between the theoretical OCV and the actual OCV. This occurs because the hydrogen leaks through the membrane, reacting directly with the oxygen thus missing out on the charge transfer the fuel cell would induce causing the reduction in the OCV.

Activation Overpotential[5]: these losses are the most significant in the reduction of fuel cell performance and one of the most actively pursued in research. Activation losses have a logarithmic decay, which are caused by the slow reaction rates on the surface of the electrode, predominantly at the cathode where the oxygen is being broken down and combined with hydrogen to form water.

Ohmic[5]: and can be thought of as an internal resistance to the fuel cell, where within this regime the voltage is linearly correlated to the current by the resistance, R. This resistance is the cumulative resistances of the electron and ion flow within the membrane, electrodes, gas diffusion layer, endplates, etc. Obtaining a low resistance is highly beneficial to improving the fuel cell performance.

Mass Transport[5]: as seen from the polarization curve is the logarithmic loss occurring when the fuel cell is operated at a low voltage and high current. This effect usually takes place at high current densities and is a difficult and compounding solution to try and solve. Reason being as you go to higher current densities you require more reactants to maintain the power draw, at the same time however you are also creating more products which reduces the amount of area for the reactants to gain exposure to the MEA.

3 Research Overview

3.1 Research Direction

Since PEM fuel cells have the widest ranges of potential applications and can be foreseeable integrated into standard portable electronics, my thesis revolves around PEM fuel cell design. I intend to create a new method of integrating fuel cells into portable electronics by re-evaluating current fuel cell design to make a PEM fuel cell with reduced mass, physical volume, and cost. Some of the main issues that need to be considered when evaluating fuel cell designs is how they deal with water management as well was combating the main forms of losses discussed in **Section 2.3**

3.2 Water issues

Concerning the water management there are two main water issues currently being researched with regard to PEM fuel cells. First is the humidification of the membrane, since the fuel cell's performance is coupled to the membrane not drying out. Methods for humidifying the membrane range from passing the reactant gasses in a stream of bubbles through water to directly applying water to the membrane. However, these forms of

external and active humidification methods are disadvantageous for portable applications, leading to increase in size, weight, complexity, and user maintenance. Therefore, trying to find ways that circumvent these methods of humidification are ideal. Also, researchers are attempting to understand more of the water transport characteristics in an operating fuel cell. This increase in understanding will yield a more sophisticated solution to the optimization for the fuel cell design to reduce or eliminate the need to humidify a fuel cell and still maintain comparable performance. Current research has shown that the key factors in the humidification of the membrane when using dry reactant gasses and no external humidification is coupled to the area of the electrode, how the electrode is made and the design of the flow field[6].

Further research also must address how water is accumulated at the cathode side of a fuel cell. It is essential to figure out how to manage this water accumulation to reduce the blocking of the reactant gases from the membrane. This water accumulation, as previously mentioned, occurs at the cathode side of the fuel cell, and is due to using graphitic carbon and metallic conductors such as titanium and stainless steel which possess hydrophilic properties, increasing the potential for water to flood and preventing uniform gas distribution to the fuel cell. Current research suggests that this problem may be prevented by applying a thin hydrophobic coating to these channels via plasma polymerization. For low current consumption situations there is not much of an effect, due to the reduced need for oxygen and reduced production of water. However, once the current demand is increased and the oxygen consumption is larger the hydrophobic thin film layer plays an important role in reducing the amount of water accumulation,

allowing an increase in available power. This coating also has the beneficial side effect of providing a physical barrier between the current collecting surface and the water, which helps prevent corrosion[7].

3.3 Overall Design and Stacking Multiple Fuel Cells Research:

3.3.1 Overall design and patents

The thermodynamic limitations of a single PEM fuel cell, governed by the Nernst equation, essentially limits the voltage output of a fuel cell to about 1.2 volts at 25C and 1 atm regardless of that cell's physical size. In contrast, the current a fuel cell can produce is directly proportional to the size, and primarily the area, of the fuel cell. Therefore, to increase the voltage output of fuel cells, it is essential to connect them in series to build up a potential difference, as shown in **Figure 8**. This drives the design solution of stacking fuel cells together. The most common format for stacking fuel cells is to vertically stack the cells, placing the anode of one cell adjacent to the cathode of another, which are electronically connected via a bipolar plate. The bipolar plate transfers the electrical charge, as well as the pathways for reactant gases and products to flow.

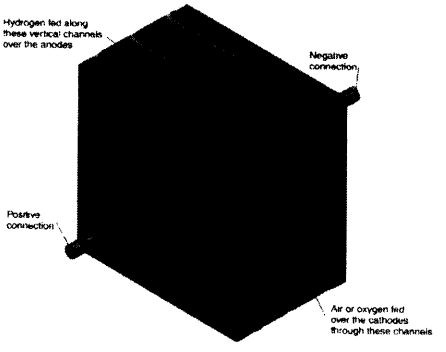


Figure 8: Conventional fuel cell stack design (Larminie, P.10)

Another variation of this conventional stacked system involves placing multiple fuel cells in a horizontal planar fashion in what is referred to as a "plaque", then stacking multiple plaques on top of each other in a style similar to the conventional fuel cell stack, as shown in **Figure 9**. This method reduces energy density when compared to the conventional stack; however, it accommodates a variety of other possibilities, such as temperature controlling capabilities. This design also allows for an increased voltage output within the stack by electronically connecting the fuel cells within the plaque in series, thus giving a voltage output ***n*** times larger then a conventional stack, where ***n*** is the number of fuel cells in a plaque[1,8].

Figure 9: Joining multiple fuel cells in a horizontal plane to form a plaque, and the plaques are then stacked on top of each other in a fashion similar to conventional fuel cell stacking methods[8].

A completely planar fuel cell design, seen in **Figure 10**, creates multiple fuel cells on a large single proton exchange membrane. This assembly is sandwiched between an anode and cathode plate, which individually isolates each cell and transfers its electrical charge to the outside of the planar fuel cell stack assembly. At this point, external electrical connections can be made to connect each of the individual fuel cells in series, allowing the voltage output of individual cells to be summed[9].

Figure 10: Planar fuel cell, using a single large proton exchange membrane and external electrical connections to put each individual cell in series with one another[9].

A more radical design, and the focus of my research, is the banded fuel cell design, where internal connections join the anode of one fuel cell to the cathode of another in a horizontal plane, as shown in **Figure 11**. This type of design minimizes components and obtains minimal volume; its versatile fuel cell placement making it ideal for portable electronics. The difficulty has been making the design robust, reliable, and effective[1,10,11].

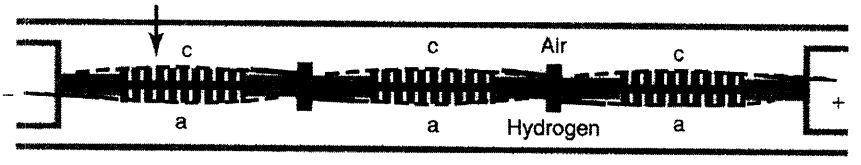


Figure 11: Banded planar fuel cell stacked design[1].

3.3.2 GDL at outer surface

In fuel cell applications for portable electronics, the shear size and weight of every component that goes into the device must be carefully scrutinized to ensure it has a direct function and purpose. Otherwise, the component adds unnecessary weight and size to the device. The fuel cell is no exception, and to make fuel cells competitive in today's world they must undergo a reduction in size, weight, and cost. One strategy to achieve this goal suggests an evaluation of every component of the fuel cell design and reduction of the

part count while increasing the functionality of each part. Before this happens, we need to see what is possible. Some research is being done to determine if the fuel cell can operate while being open directly to ambient air, thus reducing the cathode complexity by not having a flow field design. Other research is evaluating the fuel cell's ability to operate without pure oxygen. With this approach a simple cathode current collector with the middle material removed would allow the gas diffusion layer on the cathode side direct exposure to ambient air. With this setup the fuel cell was able to obtain a max power density of about 194 mW/cm^2 [12], which is enough to show not only functionality but also practicality; this power density is enough for portable electronic applications[12].

Once this group obtained proof of concept by directly using ambient air to the cathode side of the fuel cell whose current collector was in large part just the gas diffusion layer, they experimented further with the cathode structure to find a more optimal design. Within this study they tried various gas diffusion layers with varying thicknesses, additionally evaluating the effect of metallic current collector ribs placed with different spacing distances to determine the effect of the metallic cathode structure to the performance of the fuel cell. From this study it was determined that the thicker the gas diffusion layer, the less important the cathode structure became. However, with a thinner gas diffusion layer, the structure was more influential; performance was increased when the cathode structure could provide enough contact area to maintain a good connection between the gas diffusion layer and the MEA. However, the spacing could not be too small, because it reduced the amount of reactant gas reaching the fuel cell. A maximum density of 360 mW/cm^2 [13] was achieved; this is a good number to strive toward in my

studies. This paper is quite instrumental to the approach and concept that is undertaken in this research[13].

3.3.3 Air-Breathing Fuel Cell Stack

To evaluate my fuel cell performance, it is important to compare my results with published literature from other air-breathing fuel cell stack designs. In a fuel cell using 22 proton exchange membrane cells in series, each with an active area of $25cm^2$, one reported fuel cell stack is able to obtain an open circuit voltage of about 20 volts. The open circuit voltage is the voltage when no current is being drawn from the cell. This value represents an average of about 0.9 volts, similar to single-cell values reported in the literature. However, the stack was able to support only about 5 amps of current This value is somewhat low, because fuel cells exist which can obtain over 1 amp/cm^2 [15]. Therefore, with $25cm^2$ active area it should be possible to get upward 25 amps of current output from the stack. Therefore much work remains to further optimize and improve air-breathing fuel cell stacks[14].

4 Planar Fuel Cell Design

4.1 Proposed Fuel Cell Designs

Starting from a blank piece of paper trying to create different fuel cell stacking designs different from the conventional vertical stack, with one slight variation, combine the functionality of the gas diffusion layer and current collector into one component. This has the potential to reduce the part count within fuel cells, as well as contribute to the reduced volume and mass if something effective can be used for this combined approach. When combining the GDL and current collectors the general material properties required

is something porous to allow for the gas to diffuse through, electronically conductive, have high surface contact area, and low resistance. With all of this in mind, the following designs were created, as shown in **Figure 12**. The M and S designs are just another take on the current bipolar plate designs. These two options function in almost the exact same way as the current bipolar plate, these just pose a potentially easier method of manufacturing the plates since simple extrusion can be implemented with these shapes. Unfortunately, these will be thicker and heaver then current designs, so if size is not and weight are not issues, as may be the case with stationary applications, these could become viable options. However, these are eliminated from the choices since they do not suffice reducing the mass and volume constraints currently imposed.

The next two designs are both variations of a planar fuel cell concept. These planar fuel cell designs are new unique designs, which satisfy the requirement for having reduced volume and mass over the current fuel cell stacking designs. The alternating design has the simplest current collector designs, being that they are simply flat plates. However, this requires the reactants to alternate or be redirected in an alternating fashion from one cell to another, this can create a complicated manifold design to deal with the gas alternating in orientation from one cell to another. However, if alternating the reactants becomes a problem, alternating the current collectors, which is the inspiration for the Z planar design, can eliminate this. By bending, cutting, extruding, etc the current collector in this orientation the reactants manifold can be greatly simplified. Taking all of these factors into consideration, the Z planar design possessed the most potential for creating a reduced cost, mass, and volume fuel cell design, and is design selected for further detail

and research. The Z planar design will just be referred to as the planar fuel cell design for the remainder of this document.

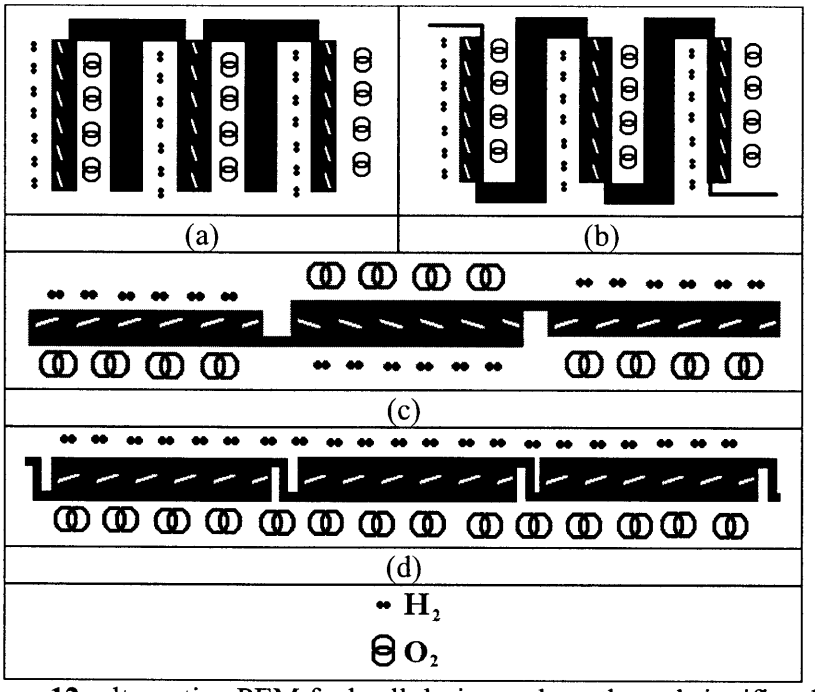


Figure 12: alternative PEM fuel cell designs where the red signifies the cathode, blue is the anode, black is the current collector, and black with strips are the MEAs, (a) M design, (b) S design, (c) alternating planar design, (d) Z planar design

4.2 'Z' Planar Fuel Cell Design

After selecting the planar fuel cell design concept, details of the design needed to be created so that they can be built and tested. **Figure 13** depicts a CAD model of a planar fuel cell design for three fuel cells connected in series. The main components of this design are the hydrogen manifold, bipolar plates, and MEAs. Hydrogen is supplied from an external source to each of the fuel cells through the hydrogen manifold, where this design as previously stated allows for the hydrogen to be on the same side for all of the fuel cells. It is a very slender low profile design which is very simple to manufacture

both on an individual testing basis as well as when implementing mass production yields. Where the most involved component is the hydrogen manifold, which would be injection molded with just any type of durable, strong, and light plastics such as polycarbonate. The exploded view demonstrates the components involved and how they will be assembled. Everything is going to be sealed with a simple application of silicon sealant on all faces that touch each other. This provides a good adhering material, accommodates for surface imperfections from any of the materials, requires no bolts which would be used to apply pressure to seal the fuel cell from leaks, the silicon sealant is also flexible which allows for the adsorption of any potential shocks and stresses that could be imposed to the fuel cell. **Figure 14** shows the front and side profile of the fuel cell to help depict what it looks like and how it works.

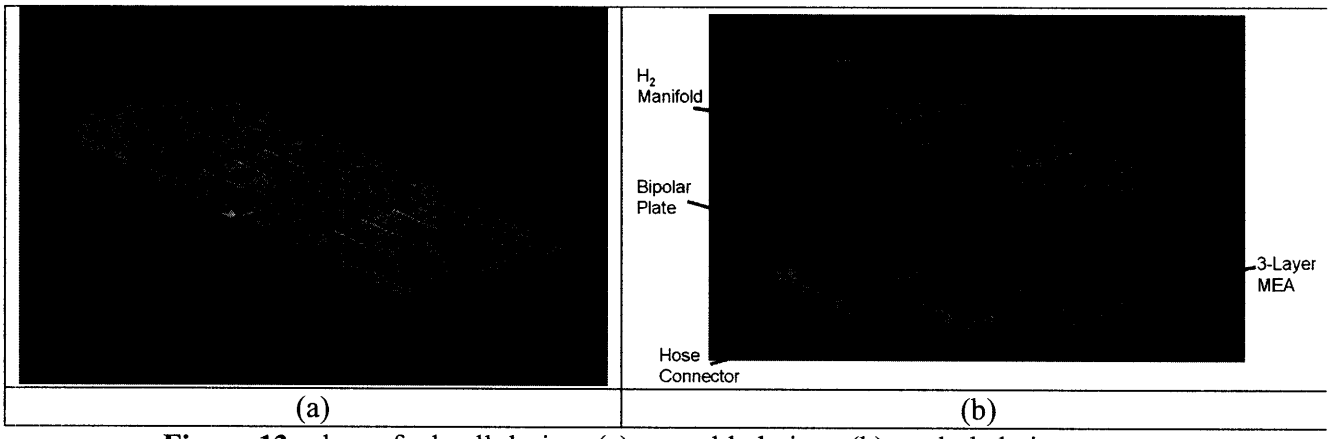


Figure 13: planar fuel cell design, (a) assembled view, (b) exploded view

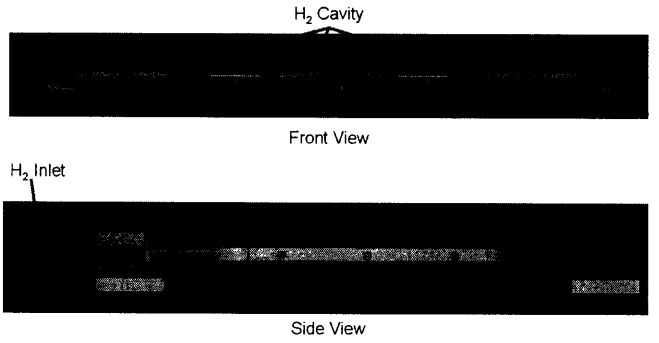


Figure 14: Front and side view of the assembled planar fuel cell

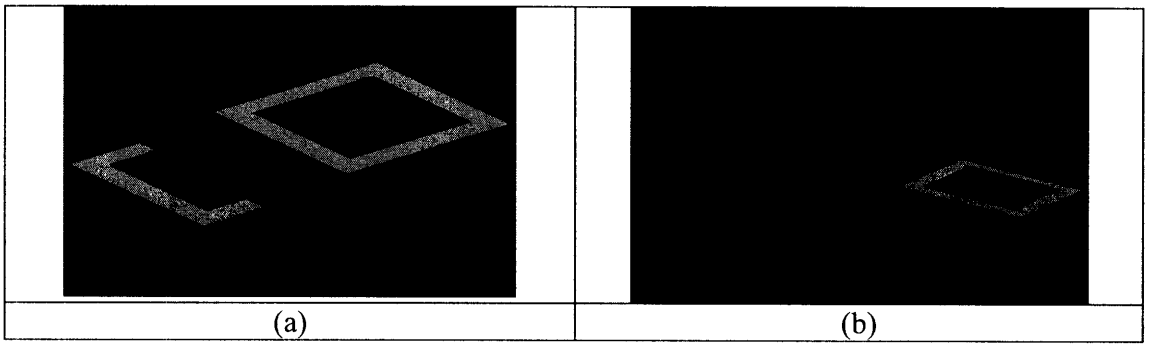


Figure 15: MEA and GDL assembly, (a) series connection between two fuel cells, (b) series connection between three fuel cells

To quantifiably examine determine how this fuel cell design has a reduction in volume, **Figure 16** starts to compare this planar fuel cell stacking design to that of the bipolar plate stacking design. For a quantitative analysis of the volume advantages from this planar design, please refer to **Appendix A**.

Figure 16: comparing and contrasting the difference between this planar fuel cell design and conventional fuel cell stacks.

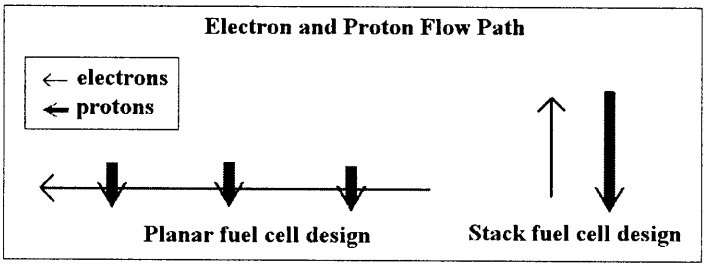


Figure 17: Electron and Proton flow paths for a Planar and Stacked Fuel Cell Design

One of the other differences between the planar fuel cell design and the stacked fuel cell design is the path in which electron and proton transfers occur as shown in **Figure 17**. With the stacked fuel cell, the electrons and protons both travel vertically throughout the stack, where the path length is governed by the height of the fuel cell stack. Additionally, with the stacked fuel cell, often the bipolar plates are made of a highly conductive material making it easy for electron transfer. With respect to the planar fuel cell design, the protons travel a distance relative to the height of the fuel cell stack, however, the electrons have to travel along the length of the stack. Therefore, if the current collectors do not have low enough resistance, the extra distance the electrons have to travel could substantially decrease that amount of possible power output from the fuel cell.

With respect to water management, the planar fuel cell relays on natural convection to remove the water. With a large exposed surface area, it will have the potential for the air to naturally evaporate the water away. However, it does not really have the capabilities of facilitating a forced convection strategy to remove the water in the way that the vertically stacked fuel cell system can, where it can just increase the flow rate of its reactants to dry out or re-hydrate the membrane. However, if natural convection is not sufficient, then for portable electronics that have a cooling system, it would be ideal to have the exhaust located underneath the fuel cell to utilize that air flow to aid in the water management for the planar fuel cell.

5 Discussion, Results

A single $25cm^2$ cell was built and tested with **Figure 18** showing the gathered data. Upon operation two good things occurred, first off, the cell was operating and functional, and secondly it obtained a comparable to literature OCV of just above 0.9 volts. However, the fuel cell is not performing anywhere near literature reported results of at least several hundred mili-amps/cm_2. Additionally the initial design objective of having the hydrogen side apply a pressure force against the GDL's and MEA did not work. A bulge was induced as anticipated, but the amount of contact force did not suffice to facilitate adequate fuel cell performance. Therefore, external forces needed to be applied to obtain data as shown below. To try and resolve the poor performance, several different humidified hydrogen experiments were conducted on the idea that the membrane could be dried out, thus greatly reducing the transport of protons through the membrane. However, minimal improvements are seen from the addition of humidification. Another clue to the problem is that there does not appear to be any mass transport limitations observed on the polarization curve. Leading to the ideas that there is something wrong with the test setup, the fuel cell design or assemble, such as a leak or short, or lastly that the ohmic losses are so large they are dominating the characteristics of the fuel cell. With the current performance of the fuel cell, we do not notice any form of mass transport limitations, this would encourage the fact that there do not appear to be any water management issues with the design. However, with improved performance and increased product generation upon further improvements of the fuel cell, water management may become more of an issue, but right now, ohmic losses seem to be the driving limitation.

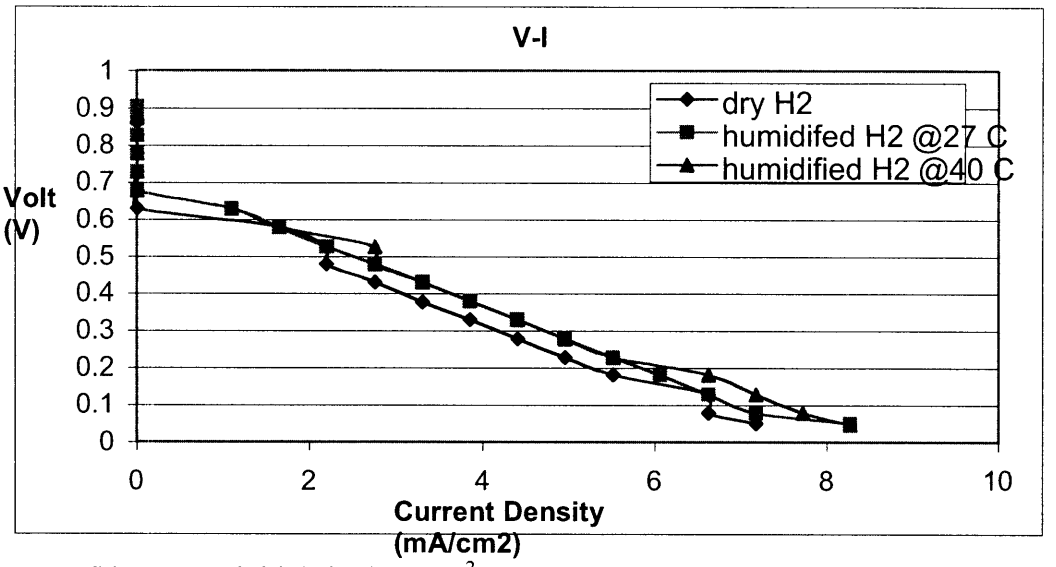


Figure 18: initial single 25cm^2 fuel cell performance where there is a slight improvement induced by adding humidification, but at the give saturation temperature, no significant difference is observed with different amounts of humidity. H2 is at designated temperature, 1atm, and 30ccpm flow rate, while the air side is exposed to ambient temperature and pressure of approximately 22°C and 1atm.

To eliminate the potential of there being something wrong with the assembly another single 25cm^2 fuel cell was assembled with close attention and verification that a short was not created and that everything was completely sealed. However, comparable results to those above were obtained. To ensure that the MEA is functioning properly, a control experiment was conducted placing the MEA into a standard fuel cell system and observed its behavior when using air and oxygen at various flow rates. The results from this controlled experiment are shown in **Figure 19**. The performance of the MEA is pretty good, it is inline with reported literature values, and it also follows the traditional fuel cell behavior described earlier. The main characteristics that can be seen are the activation overpotential, the ohmic and mass transport losses. Mass transport losses become significant once air is used as the reactant compared to that of oxygen. Which is to be expected due to the decrease in concentration of oxygen within air. A couple

interesting things to note about this data, when operating the fuel cell with hydrogen and oxygen at a ratio of 20/30 ccpm, the data shows that the fuel cell actually reduces its amount of current it can supply with a decrease in the voltage past about 0.37 volts. The reason for this is that the hydrogen was actually the mass limited media in this experimental run, where the hydrogen in the supply line was actually all consumed. Therefore as the test continued on, the fuel cell was in a severe short fall preventing it from increasing in output as shown with the hydrogen-oxygen 80/80 ccpm experiment.

Another interesting thing to note about this data is that the smaller the airflow rate, the noisier the data becomes. The reason for this is somewhat unknown but it is most likely related to water accumulation on the cathode side of the fuel cell, which is accumulating preventing airflow to the entire MEA. However when the pressure builds up, the water gets pushed out of the way giving full exposure back to the anode. This seems to make sense because the higher air flow rates can convectively transport more water out of the cathode or build up pressure more rapidly to remove any potential blockages. This is a great example of how water management is an important parameter in fuel cell operation that needs to be planned for and considered within the design. Nonetheless, the worse cases results are still better then the planar fuel cell design by an order of magnitude.

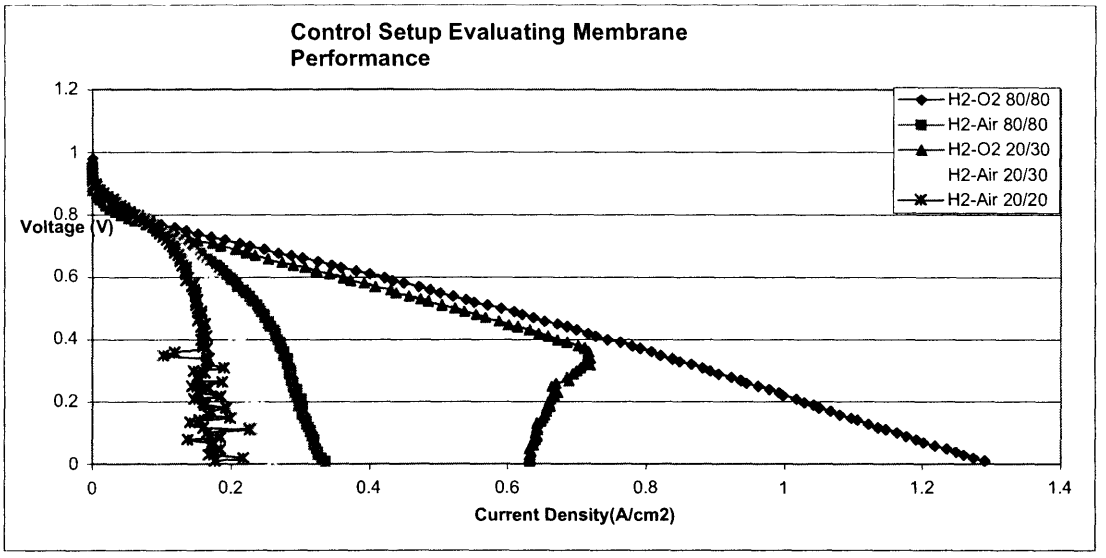


Figure 19: to try and isolate potential problems, the MEA was characterized in a standard fuel cell using both oxygen and air, where all reactants are at 1atm, and 22°C. There is a significant difference between oxygen and air, as well as when using different air flow rates.

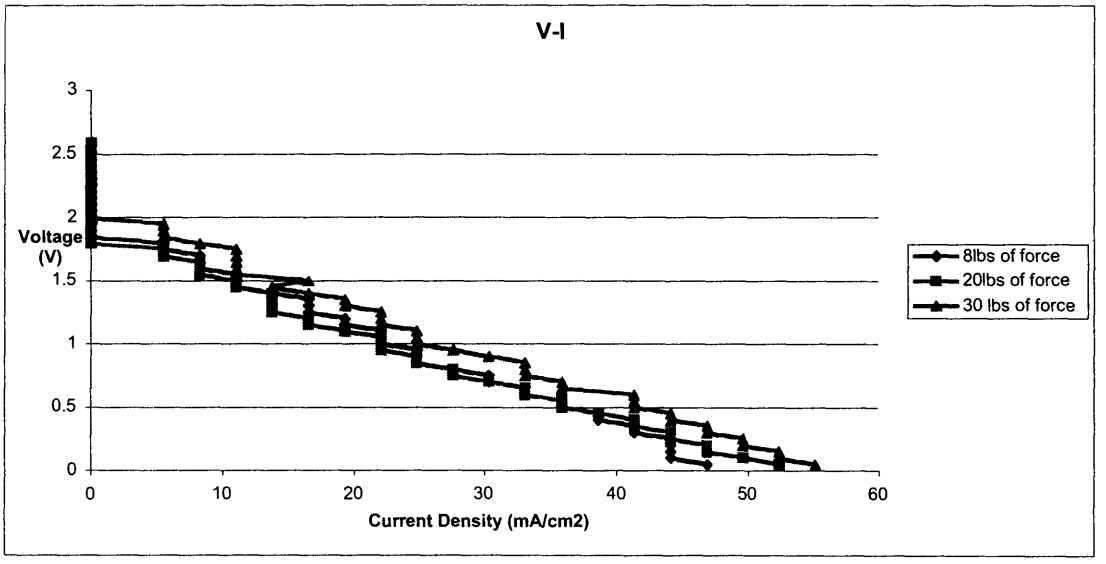


Figure 20: This is the three, 5cm2 stacked planar fuel cells, where the above data depicts the staked fuel cell performance to that amount of force being applied cumulatively to the fuel cells. This was done with the intention of determining if contact pressure correlates to improved performance. H2 is at designated temperature, 1atm, and 30ccpm flow rate, while the air side is exposed to ambient temperature and pressure of approximately 22°C and 1atm.

However the force only seems to increase the total power, it does not reduce the electrical resistance since the slopes for the V-I curves seen in **Figure 20** are approximately the same, regardless of the amount of force applied. This can mean one of several things, the force improves the amount of electrical contact points between the GDL and the electrode allowing for more power to be extracted from the cell, however it does not reduce the internal resistance of the fuel cell. Since the slopes are about the same, the effect of the compression is really only taking place initially at the activation stage of the fuel cell. Therefore, the compression could just be able to reduce the activation overpotential of the stacked fuel cell system. When evaluating the power density of the stacked fuel cell in **Figure 21**, the 8 and 20lbs power outputs are pretty similar, however when you go to 30lbs there is a 12% increase in power density. This jump between 20 and 30 lbs could indicate that there is a threshold force that needs to be applied to start observing additional power outputs. Further studies need to be conducted on this to really determine the relationship between applied force and fuel cell performance.

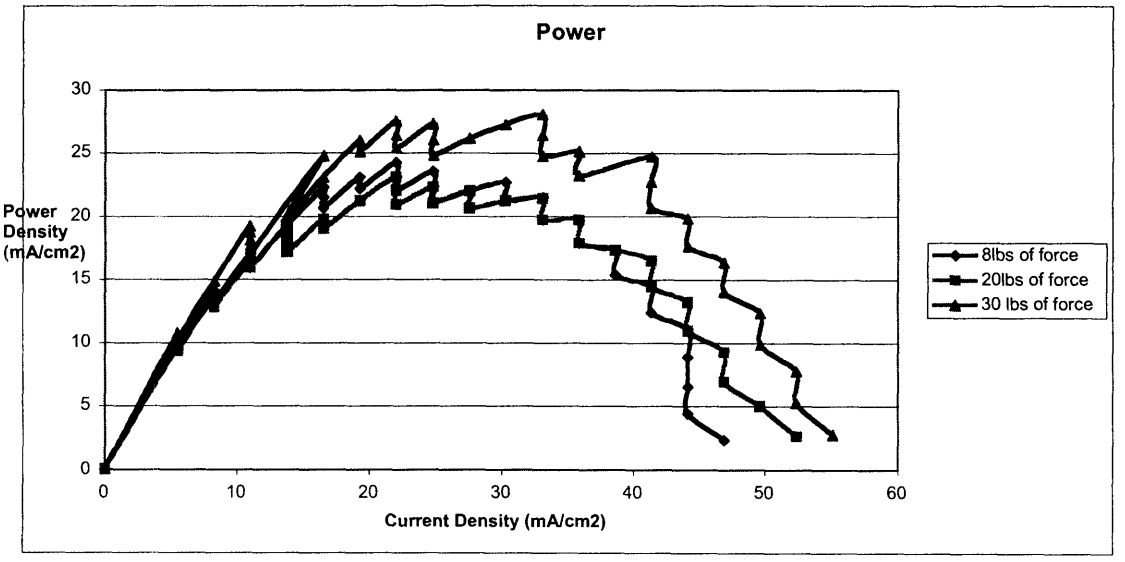


Figure 21: the power data seems to indicate there may be a threshold force

that is optimal to apply to a fuel cell while operating. H2 is at designated temperature, 1atm, and 30ccpm flow rate, while the air side is exposed to ambient temperature and pressure of approximately 22°C and 1atm.

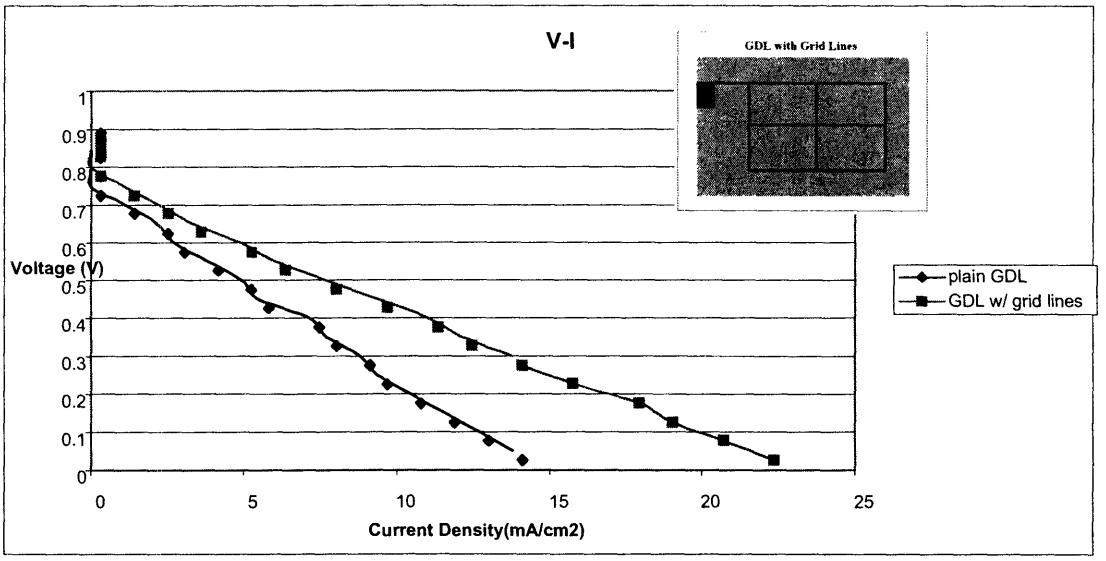


Figure 22: Polarization plot comparing single 25cm^2 fuel with and without silver epoxy grid lines placed on the GLD cells with and without grid lines placed on the GDL. H2 is at designated temperature, 1atm, and 30ccpm flow rate, while the air side is exposed to ambient temperature and pressure of approximately 22°C and 1atm. Grid line placement is shown in the upper right hand corner.

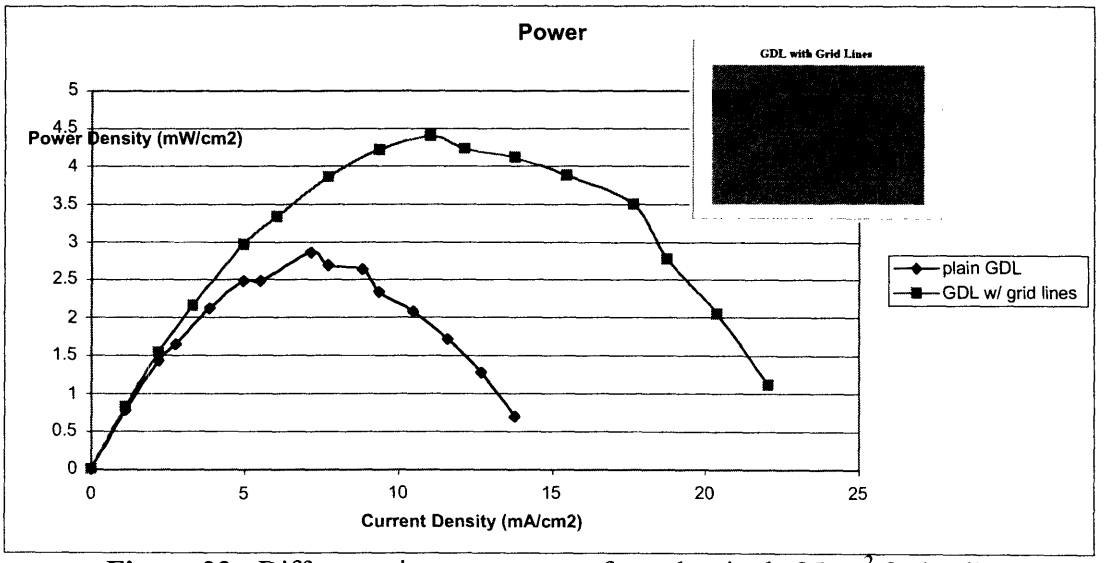


Figure 23: Difference in power output from the single 25cm^2 fuel cells with and without silver epoxy grid lines placed on the GLD. H2 is at designated temperature, 1atm, and 30ccpm flow rate, while the air side is exposed to ambient

temperature and pressure of approximately 22°C and 1atm. Grid line placement is shown in the upper right hand corner.

To try to reduce the ohmic resistance silver epoxy grid lines were placed on both gas diffusion layers in an attempt to try and reduce the path resistance the electrons have to travel. **Figures 22** and **23** show, the results from placing the grid lines onto the gdl, where the gridlines are shown in the upper right corner of each figure. These grid lines make a substantial change in the fuel cells resistance, which can be seen with a 20% reduction in the polarization curves slope. In regards to the power output, there is an increase of almost 60%. This changed had the largest beneficial impact on the fuel cell operation, which leads to the idea that the current collecting aspect of the planar fuel cell design needs to be further investigated and optimized, ensuring to develop a robust, low profile enhancement to the GDL to improve its electrical transfer characteristics. Combining this improvement with the series stacking design may yield results that bring the planar fuel cell performance to values that are comparable to the control experiment as well as reported literature values.

Summary and Prospective:

The future iterations and directions for this fuel cell development will rely on reducing the ohmic resistance of the fuel cell. Determining the amount of force that needs to be applied to compress the gas diffusion layers and the MEA is important to ensure that physical electrical contact is not in question. Additionally the integration of electrically conductive grid lines greatly decrease the ohmic resistance, developing this idea and

process will hopefully start to bring this planar fuel cell design which offers physically smaller and lighter characteristics closer to reported power densities.

Appendix A:

Assuming that the X and Y dimensions, horizontal to the paper and into the paper respectively, for each individual cell are approximately the same for both the vertically stacked fuel cell and the planar stacked fuel cell. That being the case, the only real difference in terms is the vertical height of each stack, and with the planar fuel cell the additional gap between each cell. Therefore:

$$X * Y = A$$

Which is the surface area of an individual cell, for both the planar and vertical fuel cell stacks. The remaining surface area for the planar fuel cell is driven by the gap distance, d, between each fuel cell, yielding the following total surface area, A_T.

$$A_T = n(A + (n-1)(d * Y))$$

and the total volume will be the total area multiplied by the height.

$$V_{planar} = Z_{planar} * A_T$$

where,

$$Z_{planar} = MEA + 2 * h_{current\_collector} + h_{H_2 manifold}$$

With regards to the vertical stacked volume, A is still the same, and is just multiplied by the stack height to yield the volume.

$$V_{vertical} = Z_{vertical} * A$$

where,

$$Z_{vertical} = (n-1)h_{bipolar} + 2 * h_{endplates} + n * (MEA + 2 * GDL + 2 * Gasket)$$

Then look at the ratio between V_{planar} and $V_{vertical}$

$$\frac{V_{planar}}{V_{vertical}} = \frac{Z_{planar} * A_T}{Z_{vertical} * A} = \frac{Z_{planar} * n(A + (n-1)(d * Y))}{Z_{vertical} * A}$$

An interesting thing happens with the planar design, the area that is needed to seal the fuel cells can be reduced since they can overlap with each other. This overlap can more then compensate for the gap that needs to be between each cell. Therefore if we still keep A the same value, it can easily be assumed that d is zero, if not a negative value, for simplicity, it will be assumed that d=0. This reduces the ratio too,

$$\frac{V_{planar}}{V_{vertical}} = \frac{Z_{planar} * nA}{Z_{vertical} * A} = \frac{Z_{planar} * n}{Z_{vertical}} = \frac{n\left(MEA + 2 * h_{current\_collector} + h_{H_2 manifold}\right)}{(n-1)h_{bipolar} + 2 * h_{endplates} + n * (MEA + 2 * GDL + 2 * Gasket)}$$

Where the only compounding term in the planar fuel cell volume equation, the surface area, drops out. Therefore if you optimize the surface area size for the vertical stack, the same would be true for the planar stack. Evaluating this volume ratio the fact that the planar fuel cell design has one less component offers an advantage instantly. The following are typical numbers for various components

MEA-0.1-0.3mm
GDL-0.1-0.5mm
Gasket-0.08-0.48mm
Endplate – 3-6mm
Bipolar plate- 3-6mm
Planar Cell current collector-0.1-0.5mm
H2 Manifold-2-4mm

Substituting in these numbers a range of about 9.9 –15.9 mm and 13.5 - 27mm for the planar and vertical stacked fuel cells respectively. This creates a volume reduction on the order of 25-40% with the planar fuel cell design. This correlates to an even larger reduction in mass, do to the density differences between the plastic used in the hydrogen manifold and the graphite, stainless steel, or titanium commonly used in vertical stacked fuel cells for both the bipolar plates and endplates.

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